8-1-2011

Routing protocol evaluation and development of a fully functional simulation environment for vehicular ad hoc networks

Matthew Prokop

Routing Protocol Evaluation and Development Of A Fully Functional Simulation Environment For Vehicular Ad Hoc Networks

by

Matthew J. Prokop

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Computer Engineering

Supervised by

Dr. Andres Kwasinski
Department of Computer Engineering
Kate Gleason College of Engineering
Rochester Institute of Technology
Rochester, New York
August 2011

Approved By:

Dr. Andres Kwasinski
Department of Computer Engineering, RIT
Primary Adviser

Dr. Marcin Lukowiak
Department of Computer Engineering, RIT

Christopher D. Lesser
IDVT Team Lead, Moog Inc

Thesis Release Permission Form

Rochester Institute of Technology

Kate Gleason College of Engineering

Title: Routing Protocol Evaluation and Development Of A Fully Functional Simulation Environment For Vehicular Ad Hoc Networks

I, Matthew J. Prokop, hereby grant permission to the Wallace Memorial Library to reproduce my thesis in whole or in part.

Matthew J. Prokop

Date

Dedication

This thesis is dedicated to my wife, my parents, my family and friends. Without their help and constant support it would not have been possible. It is also dedicated to my late grandfather, who has always done so much for me and expected nothing in return. You won’t be forgotten.

Acknowledgments

I am grateful for my thesis committee and the guidance they have provided throughout the entire process. I am also grateful to Harshad Phule, David Layerle and Timo Bolse for their support when I had issues.

Abstract

A Vehicular Ad-hoc Networks (VANET) is an area of wireless technologies that are attracting a great deal of interest. There are still several areas of VANETS, such as medium access control, security and routing protocols, that lack large amounts of research. There is also a lack of freely available simulators that can quickly and accurately simulate VANETs. One of the two main goals of this thesis was to develop a freely available VANET simulator and to evaluate popular mobile ad-hoc network routing protocols in several VANET scenarios. The VANET simulator consisted of a network simulator, a traffic (mobility simulator) and used a client-server application to keep the two simulators in sync. The VANET simulator also models buildings in order to create a more realistic wireless network environment. The second main goal of this thesis was to provide an evaluation of the routing protocols that are commonly used in mobile ad-hoc networks, which will apply to VANETs. Ad-Hoc Distance Vector routing (AODV), Dynamic Source Routing (DSR) and Dynamic MANET On-demand (DYMO) were initially simulated in a city, country, and highway environment in order to provide an overall evaluation.

Contents

Dedication . . . . . **iii**

Acknowledgments . . . . . **iv**

Abstract . . . . . **v**

1 Introduction **1**
1.1 Motivation 1
1.2 Thesis Statement 3

2 Related Work **4**
2.1 Architecture for Vehicle Safety Communications 4
2.2 DYMO Protocol 6
2.3 Evaluation Criteria 6
2.4 Routing Protocols 8
2.4.1 Ad-hoc On-Demand Distance Vector Routing 8
2.4.2 Dynamic Source Routing 10
2.4.3 Dynamic MANET On-Demand Routing (DYMO) 13

3 Research Work **15**
3.1 VANET Simulations 15
3.1.1 Currently Available VANET Simulators And Tools 16
3.1.2 Wireless Network Simulators 17
3.1.3 Traffic Simulation 19
3.1.4 Simulator Coupling 20
3.1.5 Simulation Setup 21

4 Simulation Setup **24**
4.1 The Simulator 24
4.2 Simulator Communication 25

4.3 The Simulations 27
4.4 Evaluations 28

5 Results and Analysis **30**
5.1 Throughput Results 31
5.2 Latency Results 33

6 Conclusions **42**

7 Future Work **45**

Bibliography **46**

List of Figures

2.1 Dynamic Local Peer Group Examples [1] 6
2.2 Two DYMO examples [2] 7
2.3 Route Discovery for DSR Routing Algorithm [3] 11

3.1 Example of a NED file 19
3.2 TraCI Connection Example [4] 22

4.1 VANET node model in Omnet++ 25
4.2 TraCI Message Format [4] 26
4.3 City Mobility Network 28
4.4 Country Mobility Network 29
4.5 Highway Mobility Network 29

5.1 Throughput in bits/second for city environment 36
5.2 Throughput in bits/second for highway environment 37
5.3 Throughput in bits/second for country environment 38
5.4 Latency in seconds for city environment 39
5.5 Latency in seconds for highway environment 40
5.6 Latency in seconds for country environment 41

List of Tables

1.1 Examples of VANET applications [4] 2

5.1 Throughput results for the high, medium and low traffic density scenarios . 34
5.2 Latency results for the high, medium and low traffic density scenarios . . . 35

Chapter 1

Introduction

Vehicles have been constantly evolving since their creation more than one hundred years ago. Some of the latest advantages include research in the field of wireless sensor networks which will allow a vehicle to communicate with other vehicles located within its neighborhood. Vehicular Ad-Hoc Networks (VANET) are a dynamic ad-hoc network, in which vehicles are continuously entering and leaving[5]. This type of network allows for communication between vehicles and with any other roadside infrastructure. Within a VANET, there are two types of networks to which nodes belong: vehicle and data. Vehicle networks consist of physical cars and the paths they take. Data networks consist of the communication between the nodes on the traffic network. In VANETs, important information can be gathered and relayed to other vehicles within the traffic network via the data network. This information can then be used within applications implemented for VANET-capable vehicles.

1.1 Motivation

VANETs are a type of mobile ad-hoc network (MANET) that allow vehicles to communicate with other vehicles and roadside infrastructure [5, 4, 6, 7]. Projects, such as Fleetnet [8] or Networks on Wheels [9], have already covered some of the aspects of vehicle to vehicle communication, however, many aspects still remain uncovered. They include high performance and efficient physical layer transmission schemes, fair and scalable medium access

(MAC) schemes, efficient data dissemination protocols, security, and routing protocols, to name some of the most critical ones [10]. The research that is proposed in this document is focused on evaluating the routing protocols that can be used in an ad-hoc network in order to provide lower latencies and more reliable communication.

Within a VANET, there can be several different types of scenarios in which vehicles are located in (e.g. city, country, highway) which play a role in the routing algorithm that should be used. With an evaluation of routing protocols, this will determine how well each tested protocol will work in the different environments. As a results, this will open doors to many applications in several domains including safety, route planning, and emergency vehicle avoidance which can all be based on simple driving events called mobility primitives[4]. Examples of VANET applications and their mobility primitives are shown in 1.1. Each of the applications are sorted based on the type of information that would be relayed to the driver, the Use Cases. The use cases are made up of different mobility primitives that the VANET application in each vehicle monitors. In order to determine if there is a traffic congestion or forward collision warning, for example, each vehicle needs to monitor the primitives of its vehicle and the neighboring vehicles. The neighboring vehicles need to send this information via the wireless ad-hoc network, therefore creating a need for efficient routing protocols to deliver the information in a quick and timely manner.

Application Type	**Use Cases**	**Mobility Primitives**				
		Change speed	Stop	Change lane	Change route	Change target
V2V Cooperative Awareness	Traffic Congestion Warning	+		+	+	+
	Forward Collision Warning	+	+	+		
	Cruise Control	+	+			
	Intersection Collision Warning	+	+			
V2V Unicast Exchange	Pre-Crash Sensing	+	+	+		
	Approaching Emergency Vehicle	+	+	+		
	Merging Assistance	+	+	+		
V2V Decentralized Environmental Notification	Road Condition Warning	+		+	+	
	Low Bridge Warning	+				
	Freezing Bridge/ Road Warning	+				
	Work Zone Warning	+		+	+	
	Fog Zone Warning	+				
	Post Crash Warning	+	+	+	+	
	Incident Detection	+	+	+	+	+
I2V Communication	Curve Speed Warning	+				
	Speed Limit Warning	+				
	Stop Light Assistance	+	+			

Table 1.1: Examples of VANET applications [4]

One of the possible applications of VANETs is trip routing that utilizes different conditions on the roads to plan the best route. Drivers could choose to plan routes based on fuel efficiency, distance, or even road conditions (i.e. congestion, slippery pavement, etc). In order to determine the best path based on a road condition, the possible paths need to be evaluated from the vehicle of interest by communicating with the vehicles on those paths. This will allow the vehicle of interest to get a view of the roads and decide on a path. This can be done, except when there are long distances or gaps between VANET-ready vehicles which prevent successful vehicle path routing. The reason that the path routing is obstructed is because the VANET-ready vehicles cannot communicate with other VANET-ready vehicles which does not allow for the information to be communicated. In order to make this process more successful, three chosen routing protocols are evaluated in this work which helped determine which protocols work the best in the different topologies.

1.2 Thesis Statement

The goal of this thesis was to examine the effects of message routing in the data network of a VANET when a vehicle is located in different traffic topologies. Along with the provided results, a complete analysis examined how the different traffic environments effect the VANET's throughput and latency. In order for a vehicle to successfully plan a route, it needs to communicate with the vehicles on the roads ahead of it. Gaps between vehicles cause VANET-ready vehicles to loose communication with each other, which causes the applications to not work. This can be a concern, for example, when trying to plan a route based on traffic congestion. Due to the lack of simulation tools for VANETs, this Master's thesis also provides an easy to use simulation environment with an in-depth study of available routing protocols in varying road topologies.

Chapter 2

Related Work

Some research has already been done in the areas of VANET applications and traffic safety. The following sections will give a brief overview of some of this research, which will aid in the research for this project.

2.1 Architecture for Vehicle Safety Communications

One of the issues associated with VANETs is the organization of neighboring vehicles/nodes. Proposed in [1], Local Peer Groups (LPGs) can be used as a first step for providing almost instantaneous communications for vehicle safety communications.

In order for Vehicle Safety Communications (VSC) to work properly, cars cannot simply be equipped with wireless communication hardware and deployed onto the vehicle network. This will result in data network problems, especially data network interference as neighboring vehicles try to send out warning messages with no transmission guidelines. By grouping vehicles, message transmission and relaying can easily be coordinated along with controlling the range and direction of messages.

LPGs provide tight coordination between vehicles in the same area and looser coordination of vehicles in the neighborhood. Two basic LPGs have been proposed by [1]: stationary LPG and dynamic LPGs. Stationary LPGs are location based and well defined, however, they do require that nodes contain a GPS device to determine LPG membership. The goal of stationary LPGs is to break roadways into groups based on zip codes. Dynamic

LPGs consist of vehicles in the immediate vicinity to form an LPG based on radio coverage in which nodes can leave or join at random. Two forms of a dynamic LPG can be used: LPG with Relative Ordering and LPG with Linked Equivalent Cells. LPG with relative ordering use a vector to define a vehicle's location in the LPG, similar to an index for an array. LPGs with linked equivalent cells (LECs) are used in high density areas in order to cut down on overhead. The main purpose behind the LEC is to assign an LPG to vehicles that are traveling together and have similar radio coverage.

LPGs use different types of control packets to collect and maintain group membership information. Within an LPG there are three types of nodes: Group Head, Member, and Border Node [11]. A group head (GH) is the LPG controller and can change at any time. The GH sends out a heartbeat message in order to define the LPG membership. When a member node receives the heartbeat, it will rebroadcast the message and reply to the GH with a membership request message. In order to avoid creating too large of an LPG, the heartbeat contains a hop limit which is the maximum number of times the message can be re-broadcasted. The boundary nodes, which are member nodes as well, are chosen nodes that can overhear control packets from a neighboring LPG.

There are two types of routing related to LPGs. Intra LPG routing takes place within each individual LPG and is table driven[11]. As the GH sends out the heartbeat messages, the member nodes that overhear the messages use the node information within the heartbeat and member responses to build its routing table. The farther the messages are relayed, the more detailed the routing tables get. Inter LPG routing uses on-demand routing principles but does not flood the network with route requests [11]. The routes traveled within intermediate LPGs is still handled by the intra LPG routing protocols. Travel between LPGs is made possible by the boundary nodes. The boundary nodes overhear the neighboring control packets and trigger routing updates for known remote destinations within their LPG.

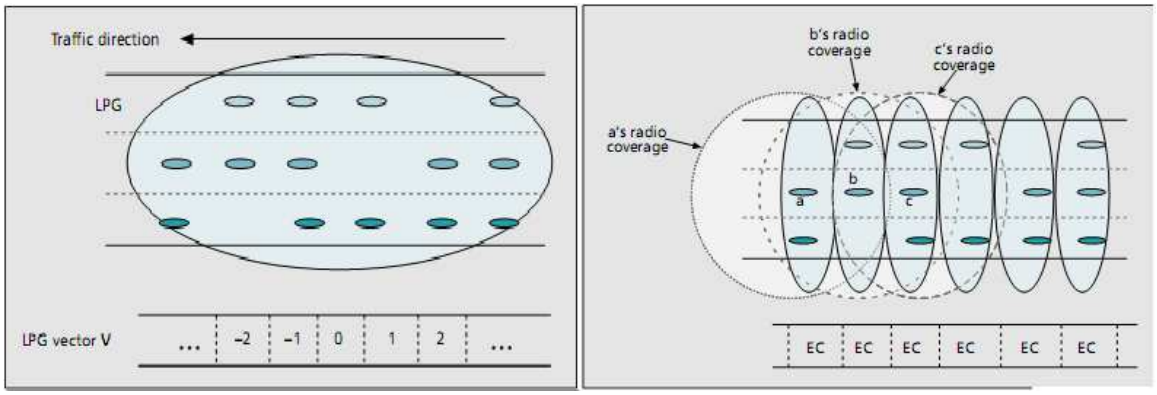


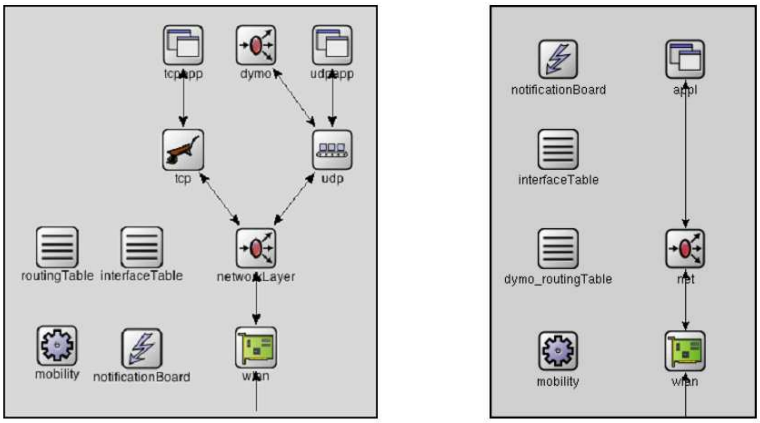
Figure 2.1: Dynamic Local Peer Group Examples [1]

2.2 DYMO Protocol

Proactive, reactive and hybrid protocols are the three different categories of routing protocols for ad-hoc data networks, according to [2]. The first is a proactive routing protocol, which relies on the periodic broadcast of data network topology. This type of protocol ensures that all nodes always have an updated knowledge of paths to other nodes. In order to do this, a large amount of data network resources have to be use, which can severely limit the amount of data that can be transferred. The second category, reactive routing protocols, can be viewed as a solution to proactive routing protocols because they only search for a route when one is needed. Some popular reactive protocols are DSR, AODV, and DYMO. Lastly, hybrid routing protocols are a combination between proactive and reactive protocols. The last protocol, hybrid protocols, exploit the fast delivery of packets from the proactive protocols and the low overhead from the reactive protocols. A typical example is the Zone Routing Protocol (ZRP)[2].

2.3 Evaluation Criteria

In [2], Christoph Sommer presents some necessary criteria that can be utilized in the simulations of ad-hoc routing protocols. One of these criteria is a proper simulation environment that can accurately simulate a wireless network. For this, Omnet++ will be used to



(a) full-featured (b) minimal

Figure 2.2: Two DYMO examples [2]

simulate the ad-hoc wireless network along with the INET Framework. INET is a freely available extension for Omnet++ which comes bundled with simulation modules. It provides modules to simulate the various layers of the Internet protocol suite (e.g. TCP, UDP, IPv4, etc...). A mobility framework was later added to the INET framework to help aid in modeling the spatial relations of nodes.

In order to properly evaluate the protocol, two models were made to use the routing protocol in an Omnet simulation. The two implementations are shown below in Figure 2.2. A full featured and minimal implementation are provided for the reasearch in [2]. For the DYMO protocol, [2] uses the following issues as the different criteria for evaluation:

- Data Network topology and mobility issues
- Parameter settings and traffic patterns
- Performance metrics
- Validation
- Simulation control
- Analysis of simulation results

2.4 Routing Protocols

Some work has already been done toward the development of VANET routing protocols. Some of the protocols that can be associated with VANETs are Ad-hoc On-Demand Distance Vector (AODV), the Dynamic Source Routing (DSR), and the Dynamic MANET On-demand routing protocols (DYMO).

2.4.1 Ad-hoc On-Demand Distance Vector Routing

AODV is a routing protocol that was designed to be used with mobile ad-hoc networks, which is the main reason for it being used[12]. The following merits of the AODV routing protocol are also the reasons for its use in this work.

One of the key features of AODV and all other reactive routing protocols is that they are not table driven. This means that routes are only created and maintained when there is a need for that route (i.e. a source Node S, needs to send a message to a destination Node D). Proactive routing protocols use a table to maintain routes over the network and require a lot of overhead to keep this up to date. The table contains a partial copy of the network topology as well as the cost between nodes. For the AODV protocol each node maintains a table that contains the following information [13]:

- Destination
- Next hop
- Number of hops
- Destination sequence number
- Active neighbors for the route
- Expiration time for this entry

The expiration time is a key feature of AODV because it helps to keep routes up to date. After the expiration time, or lifetime, is exceeded the node will delete this route from its table. If a route is frequently used then it will be updated each time a message is sent using that specific route. The update will simply take the current time and add a paramter, called the active route timeout, to it [12]. This will prolong the amount of time the route stays active.

If a route is not contained in the node's routing table then a proces called Route Request (RREQ) begins. The RREQ process floods the network with RREQ messages until the destiation node or hop limit is reached. The RREQ messages that the nodes send out contain the following [14]:

- Source Address
- Request ID
- Source Sequence Number
- Destination Address
- Destiantion Sequence Number
- Hop count

When a node wishes to initiate a RREQ, it will broadcast a RREQ message to all of its neighbors. When receiving a RREQ message, each node will check the source address and request ID so it does not process the same RREQ more than once. If the message has not been processed yet the node will check its routing table and perform one of two options. If a route already exists in the table with a sequence number greater than the one in the RREQ or the current node is the destination, it will generate a route reply (RREP) message to be sent back to the source. Otherwise, the node will rebroadcast the RREQ with an update hop count. A RREP message is used to reply to a RREQ because a valid path has been found.

An RREP contains the following information:

- Source address
- Destination address
- Destination sequence number
- Hop count
- Lifetime

In the event that a node goes missing from a path (it no longer exists) a route error (RERR) will be sent out. When a node receives a RERR message, it will update its routing table by removing the node that is causing the RERR and any related routes. The purpose of this is to eliminate the use of the bad route in the future.

The most important feature of AODV routing is the use of sequence numbers [12]. The sequence number helps to keep routes in the routing tables fresh. When a nodes receives a message with a route and a sequence number it will compare what is in its own routing table. If the sequence number in the message is greater than what is in the nodes table, the route will be replaced because the new route is newer. Sequence numbers also help to eliminate nodes from creating the infinite loop problem [15].

Another feature of AODV is the use of HELLO messages[12, 16]. These messages are broadcasted to all nodes within a source node's transmission zone and can be used to learn of new neighbors and other changes in topology such as link breaks. HELLO messages are only sent out periodically and when a node fails to receive messages from a known neighbor then the path is marked as broken.

2.4.2 Dynamic Source Routing

Dynamic Source Routing (DSR) is another routing protocol that was specifically designed for use in multi-hop mobile ad-hoc networks[3]. Like AODV, DSR is a completely self organizing algorithm that can configure itself without the use of any central infrastructure. Unlike AODV, DSR only has two mechanisms:

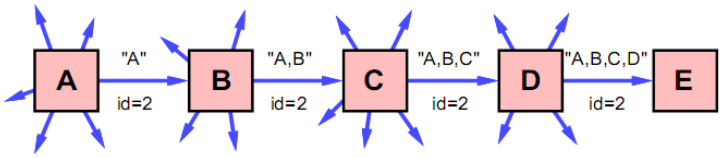


Figure 2.3: Route Discovery for DSR Routing Algorithm [3]

- Route Discovery: the process of discovering a route from a source to a destination.
- Route Maintenance: allows for the topology of the network to change and a nodes routing table to remain fresh.

Route discovery and maintenance do not run on a periodic schedule, rather they run only on demand. AODV uses periodic messages (HELLO message) to learn of the wireless network's topology, however, DSR does not use any type of periodic packets or messages at any level. The purely on demand behavior of the DSR routing algorithm allows it to cut down network overhead compared to algorithms that do use it[3]. DSR allows for the nodes to learn of changed topology quickly because a node has the ability to cache routing information overheard on the network. This becomes quite useful because multiple routes that lead to the same destination can be stored in a node's routing table. In the even that a transmission fails, a node can try another stored route rather than initiating another route discovery.

Route discovery is the process that the DSR algorithm uses to find a route to send a packet from source to destination. Normally when a node wishes to send a packet to some other node the sequence of hops that need to be taken are put into the message. When no route is present the source node transmits a route request (RREQ), similar to AODV. Each node broadcasts the message until it reaches the destination. Once at the destination node, that node will send back a route reply (RREP) to the source.

As shown in the Figure 2.3 node A wishes to send a packet to node E. Node A initiates a route discovery with an RREQ that contains node A as the initiator, an empty route record list, and a unique request ID. As each node broadcasts the request to all nodes within range,

the route is built because each node appends itself to the route record in the RREQ. A node will drop the route request if it has seen another route request from the same initiator with the same request ID or the node's address is already present in the route record.

Once the route request reaches the intended destination, the destination node will send a route reply back to the initiator. In the Figure 2.3 node E initiates the route reply by examining its own route cache for a route back to node A. If a route exists it will use that route, however, if no route exists a new route discovery must be initiated. To avoid the possibility of infinite route discoveries, node E will piggyback the route reply on the new route request [3]. For protocols that support bidirectional links, such as IEEE 802.11, the destination node will use the reverse route that is located in the route request. This prevents flooding the wireless network with route requests, however, it does not allow for nodes to learn of new and more efficient paths [3].

In the event that a node cannot successfully transmit a packet to the next hop, it needs to perform route maintenance. When forwarding packets along a source route, each node on the route is responsible for the successful transmission of the packet to the next hop. This reply can either be done by using an existing part of the MAC protocol in use or done passively [17]. In the Figure 2.3, node B can confirm the receipt of the packet to node C by listening to see if node C tries to forward the packet again. A route error message is sent out in the event that a node does not receive a successful transmission. The route error message is sent back to the original sender with the location of the broken link so the appropriate change in the table can be made.

One feature of the DSR routing algorithm is that is allows for nodes to cache route information that is passed along in route requests or route replies. Nodes can gather this information by messages addressed to that node, messages that were broadcasted, or messages obtained while a node's network interface is in promiscuous mode. This allows nodes to learn of the changing network topology, however, it can cause an issues if routes are assumed bi-directional when they are uni-directional [3]. Another feature of DSR includes the ability to salvage a packet. In the event of a route error a node will still send out a

route error message to the original sender but it may not discard the packet. Instead, the node will look for a route in its own route cache and try to send the message to the original destination.

2.4.3 Dynamic MANET On-Demand Routing (DYMO)

The final routing protocol that was used for evaluation is the Dynamic MANET On-Demand (DYMO) routing protocol [18]. The DYMO routing protocol is another protocol that is designed for use in mobile wireless ad-hoc networks. Unlike the work in [19], this implementation will be integrated right into the network layer and not as part of the application layer. Just like DSR and AODV, DYMO consists of two main operations: Route Discovery and Route Maintenance.

DYMO route discovery is performed similar to the AODV and DSR routing algorithms. When a node needs to send out a packet to another node it will first search its route cache or routing table to see if an up to date route exists. If one does, the source node uses that route to send the packet to its destination. However, if a route does not exist the node must go through a process to find a path to the destination, called route discovery. The source node creates a route request (RREQ) message to send out to all neighboring nodes. The RREQ contains the following information [20]:

- Destination Address
- Sequence Number
- Hope Count
- Next Hop
- Next Hop Interface
- Is Gateway
- Prefix

- Valid Timeout
- Delete Timeout

The source node will then send out the RREQ via broadcast to all of the surrounding nodes. The receiving node will look at the packet to make sure that it has not seen it before and if it has the packet will be discarded. If it has not been seen before, the node will then start to look at the information contained inside of the RREQ. If the routing table does not contain any information for the originator, the node will create a spot for it and update the the data in the RREQ. If an entry already exists but the sequence number indicates there is out of date information then the RREQ is dropped. Lastly, if the sequence number indicates there is new information in the RREQ then the data in the routing table is updated and the RREQ is passed on. Once the RREQ reaches the destination node, that node will then form a route reply (RREP) that contains the new route and is sent back along the reverse path.

Route maintenance is the other operation that the DYMO protocol does. The only time that route maintenance is done is when a node receives a message that it does not have a route for. In other words, the 'next hop' node could have moved out of range or its network interface could be down which would prevent that node from receiving messages. Route maintenance is invoked when a data packet cannot be delivered to the next hop because no path is available. The node that must perform route maintenance will create a route error message (RERR), it will look at the node that is causing the issue and create a list of all entries in the routing table that depend on that node as the next hop. The RERR is then sent back to all nodes that are affected by this network issue.

One feature to note about DYMO is that it does not support uni-directional paths [18]. This is usefule when caching routes overheard in the network because it can use those routes to forward packets, providing they are valid at the time of need, without the use of route discovery. Another feature of DYMO is that its nodes will cache routes similar to the way nodes in DSR do. As RREQs and RREPs are overheard, the nodes that are eavesdropping can add additional information to their routing tables from the received messages.

Chapter 3

Research Work

Vehicular ad-hoc networks are becoming a useful tool for safe and comfortable driving, however, many challenges are still encountered when trying to implement tools for VANETs. Data transfer and applicable routing protocols are the main topics that are covered in this research.

3.1 VANET Simulations

One of the primary goals was to develop a simulation tool that will allow for accurate simulation of VANETs as is needed by this research and future endeavors. Current VANET simulation tools are either not publicly available or not efficient for examining VANETs with many changing variables [21]. The tools that are not publicly available were developed by companies to accommodate for their needs with VANET simulations. Tools that are publicly available are not suitable for the more complex VANET simulations because they are based on mobility trace files. This can be an advantage if the simulation environment never changes, however, when the need arises to modify environment variables that cause a change in node mobility paths, the trace files need to be regenerated in order to work with the network simulator.

3.1.1 Currently Available VANET Simulators And Tools

CanuMobiSim Communication in Ad Hoc Networks for Ubiquitous Computing (CanuMobiSim) is a java based mobility simulator that can be used towards simulation of VANETs. CanuMobiSim is not a data network simulator, rather it provides the traces that can be used to map mobility of vehicular nodes. CanuMobiSim can generate traces for the smooth mobility model, pedestrian, graph walk and several others [22]. One of the drawbacks of this tool is that it lacks the ability to create random mobility traces. This tool works by taking data from Geographical Data Files or user defined maps and extracts the node mobility to create the trace files that can be used with NS-2.

NS-2 and NS-3 NS-2 is a network simulator that has been around since the late 1980s[23]. This simulator works by executing code written in C++ and OTCL. Based on the execution of the code it will generate a file that is used by the Network Animator (NAM) to put the nodes in their proper places and accurately simulate the network. NS-2 includes many libraries to simulate many wireless networks, however, it initially lacked the capability to simulate multiple radio interface[23]. With technology changing, a later release offered support for this important aspect.

A newer version of NS-2, written in purely C++ has been released in 2008 called NS-3. NS-3's initial release was closely followed by nine other releases that added more functionality onto the base program. Its main goal was to develop an open simulator that could be used for modern networking needs. NS-3 contains support for multiple models, including WiFi, WiMAX, and static or dynamic routing protocols. NS-3 releases a new stable version of their software every three months with newly developed and validated tools [24].

GlomoSim and Qualnet Glomosim is another very popular network simulator but not quite as popular as the previously discussed NS-2. Glomosim's main focus for network simulations is on wireless networks [22]. Coded completely in Parsec, Glomosim's protocols must be written in the same language, which creates a problem if one is not familiar

with it. One of the positives of Glomosim is that it is able to simulate large networks due to its ability to split work between CPUs. All the work needed for a simulations will be divided up into separate processes which will also create less work and quicker simulations. For most simulations in Glomosim the Random Waypoint Mobility model is used, however, there have been other projects that allow Glomosim to use other models as well. The GEM project is a major project that helps Glomosim have more realistic simulations [25]. Glomosim was later re-released as a commercial version called Qualnet.

QualNet is written entirely in C++ and is modelled as a state machine, as most other simulators. It has the ability to run on various platforms, including Mac and Windows. Along with the many libraries that Qualnet is equipped with, it also supports the ability to create 3D visualizations that can support up to 20k nodes [22].

3.1.2 Wireless Network Simulators

Omnet++ is a C++ program written to simulate communication networks, multiprocessors and other distributed or parallel systems[26]. This simulator is open sourced and is free for non-profit use. Omnet++ was designed to do the following [26]:

- Enable large scale simulations with reusable models.
- Provide easy tracability and debugging.
- Simulations software should be modular.
- Analyze input and output files with common software.

In order to provide a large scale simulations with reusable models, Omnet++ uses modules to develop the different components of the simulation. Simple modules are the most basic modules as they provide extremely basic functionality. Compound modules are created by grouping simple modules together to create an object with a complex functionality, such as a vehicle equipped with a IEEE802.11b radio. Modules contain different configuration parameters that can be passed to its submodules to customize the module. Parameters

can be represented as strings, numbers or pointers. In order for the modules to communicate with each other they exchange messages. Each message contains a time stamp and any data relative to the communication between two modules. Modules are connected to each other with a 'connection' module to the appropriate gates.

Omnet++ monitors the communication patterns of the VANET nodes along with the use of the INET Framework. A framework is a plug in for Omnet++ that contains many modules (network interfaces, different layers, applications, example nodes, etc) for use in simulations. This INET framework provides the necessary modules to simulate different types of networks and network layers[27], including the IEEE802.11b wireless ad-hoc network used in this work. The Obstacles project, combined with the INET framework, gave Omnet++ the ability to model buildings, which allowed for a more realistic simulation of a VANET. This will not be as important in a rural setting, however, in a city environment there are many buildings that will play into how the wireless signals are transmitted.

Modules in Omnet++ are connected to each other's input and output gates with the use of simple 'connection' modules. These connections are all defined in a file that uses the NED language, as shown in 3.1. Omnet's own topology description language is what the user uses to define how their models will be set up [26]. Similar to how modules were designed to be reusable, NED models are also reusable and designed to work with other NED files to create much larger models. A nice feature of Omnet++ is that it uses a two way editor to create and modify the NED files that make up the environment. One option for NET editing is through a generic text editor, which Omnet++ provides or the use of a third party editor. The second option for editing is through Omnet++ GUI that allows for dragging and dropping of pre-defined and user-defined NED files and connections. In figure 3.1, the uppper portion of the image shows the graphical editor while the lower portion displays the same model in text version.

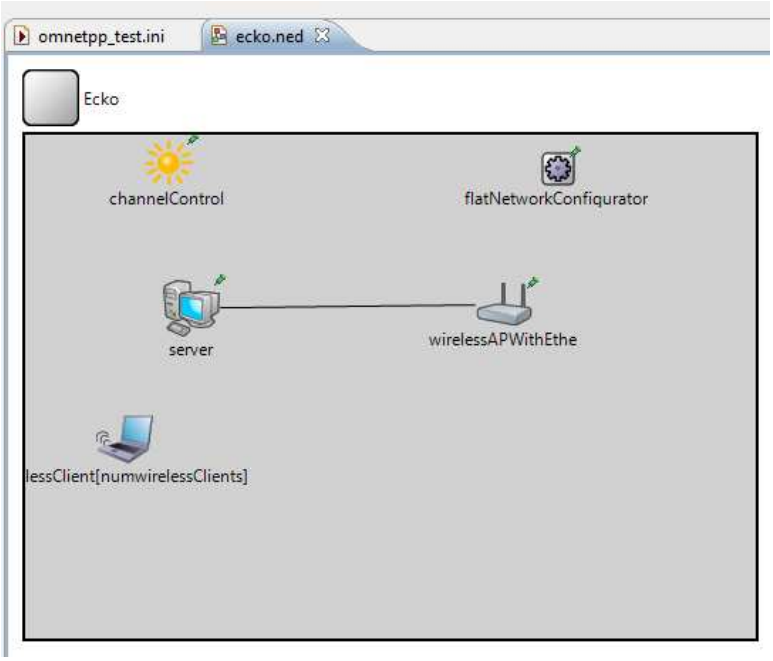


Figure 3.1: Example of a NED file

3.1.3 Traffic Simulation

Simulation of Urban Mobility(SUMO) is a C++ application developed to simulate the movement of objects along a road network. It is a free and open sourced simulator that was originally developed for use of the employees of the Institute of Transportation at the German Aerospace Center. Along with being able to model small areas, SUMO is also capable of modelling traffic in large networks, such as cities or highway networks, without any changes.

SUMO simulations are considered to be multimodal, meaning that every object in the simulation is simulated [28]. Not only are cars simulated, SUMO also takes into account any public transportation system, train networks, and even traffic lights if desired. Each object in the simulation is modeled individually, so no two vehicles are the same. During each simulation step the values for every node are updated. One of the drawbacks of SUMO is that the user is limited to a one second simulation step. During simulation, the vehicles must obey basic rules just like in a real traffic environment. Nodes must follow

the maximum speed for a road, right of way to other vehicles, and even how fast or slow a vehicle can speed up.

The latest version of SUMO offers the following features [28]:

- Collision free vehicle movement
- Different vehicle types
- Multi-lane streets with the ability to change lanes
- Right of way at intersections
- Raw output for each simulation
- Input from XML files

SUMO comes with quite a few tools that can help create any type of simulation. Some of the most useful tools are the network generator and the route generator [**?**]. SUMO allows for the import of freely available maps from sources such as Open Street Maps [29], however SUMO also comes with its own network generator. Netgen[30], the tool to create maps, and Netconvert[30], a tool to import maps, do not include route files in their output. Route files instruct a vehicle where to go next and need to be generated with Duarouter, SUMO's route generation tool [30]. SUMO can also incorporate buildings, parking lots, and other land marks with the use of Polyconvert. This tool can extract the needed information from the imported map and will place it in an XML file, buildings.poly.xml, similar to the way the other tools do, which will be used during simulation.

3.1.4 Simulator Coupling

To accurately model a VANET, Omnet++ and SUMO are connected with a technique to synchronize node movement between two simulators. The Traffic Control Interface (TraCI) is used to couple the simulators. Previous VANET simulation approaches used mobility traces that the network simulator read in [5, 31]. The second approach uses a simulator that

has the network and traffic simulators built in together, such as Groovesim [32]. The third approach uses techniques similar to TraCI that couple the two simulators together. This approach was chosen for this work because all software used in free and open source. The separation of the simulators also allows for changes in the overall simulation environment ot be made without having to regenerate trace files.

TraCI works in a client-server manner [4]. The TraCI server runs on the client PC as a third application; it waits for TraCI clients to establish a connection. The TraCI client is built into the network simulation, and in Omnet++ is part of the network node that is being simulated. When the network simulation is started, the nodes will connect to the server and wait for commands to be sent. Omnet++ will send a synchronization message to the server to tell the traffic simulator, SUMO, to advance one step. SUMO will then send the simulation results (vehicle coordinates) back to the network simulator.

Based on the work of [21], the network simulator was coupled with the traffic/mobility simulator through a TCP connection. This allowed for each simulator to work independently while maintaining a connection with the other simulator for accurate results. The basic setup of this simulator remains relatively simple. The network simulator (Omnet++), which was the master simulator, performed two essential tasks. The first is to maintain the connections between the nodes in the wireless ad-hoc network. The network simulator also controls the timesteps between the two simulators which ensures that neither get out of sync. Its task is to instruct SUMO when to advance to the next step. Once SUMO completes its next simulation step, it sends back the updated location of all the nodes in the traffic network. Omnet++ will then update the locations of the nodes in the network and perform the necessary communication steps. Figure 3.2 shows an example of how the client and server interact.

3.1.5 Simulation Setup

With the two simulators successfully coupled, there was still more to be done. A wireless network, traffic map, and obstacles in the wireless environment were created in order to

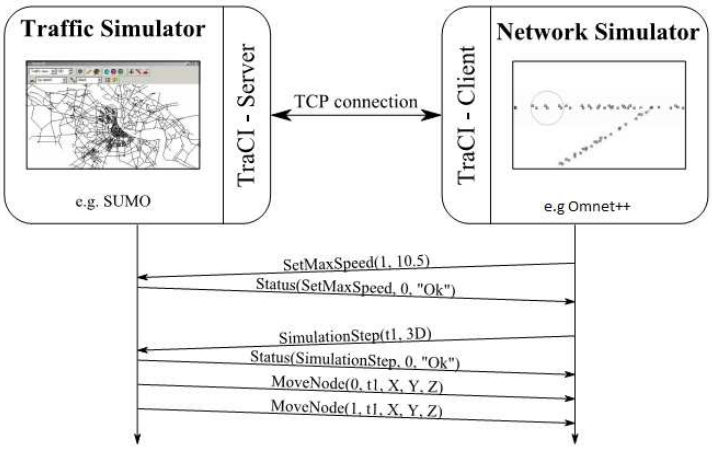


Figure 3.2: TraCI Connection Example [4]

fully simulate a VANET. The wireless network was setup to be based on the IEEE802.11b standard, which is commonly used in VANET simulations [27]. The maps for the traffic simulation consisted of three different environments. The purpose of using multiple traffic environments was to expose the routing protocols to a variety of topologies rather than just one. The first environment is a small area of a city that consists of blocks that are 100m by 100m and contain buildings in each block. The second scenario that will be used is a country environment. This environment has streets that go off in random directions and have open spaces between them. They are not placed as close as the city environment since country roads are much farther apart. The final traffic environment is a highway environment, which consists of two two-lane roads that run parallel. Each road will act as the highway lanes and consist of vehicles moving at a fast pace in opposite directions.

In order to accurately simulate the city environment, buildings needed to be added to each city block. A separate work from [19] and work from Harshad Phule [33] model buildings in a wireless network. In [19], buildings are integrated into the map for a wireless network with two moving nodes. Phule takes the work from [19] and expands it by implementing the use of building as obstacles in this work's developed VANET simulator. The buildings that were placed in each city block act as obstacles by reducing the range that nodes can transmit a packet. This allowed for nodes on opposite sides of a building to

remain unknown to each other except through the use of multiple hop messages.

Chapter 4

Simulation Setup

The setup of the simulations is key to reproducing the results gathered in this work. The following sections will outline the setup of the simulator and the simulations.

4.1 The Simulator

The simulator consists of several parts: the network simulator, the mobility simulator, TraCI, the obstacle simulator, and the routing protocol interface. In figure 4.1, the basic layout of each VANET node is shown. It consists of a network interface card, network layer, transport layer, application, and the routing protocol interface.

Each node in the simulation contains several major parts, the first part is the wireless network interface. Each network interface card supports IEEE 802.11b at a bitrate of 11Mbps. Each transport layer supports UDP only and is connected to a simple UDP application that simply sends a message of 256 bytes to a specified node every quarter of a second. The mobility module that is located in each node is what will interface Omnet++ to the TraCI server in order to provide synchronization to the mobility simulator. Lastly, the manetRouting module is the interface for the routing protocols. The manetRouting module allows the user to quickly change between routing protocols by changing a parameter in the Omnet++ simulation configuration file (omnet.ini) prior to starting the simulation.

In the NED file for the network environment, all of the basic modules need to be present,

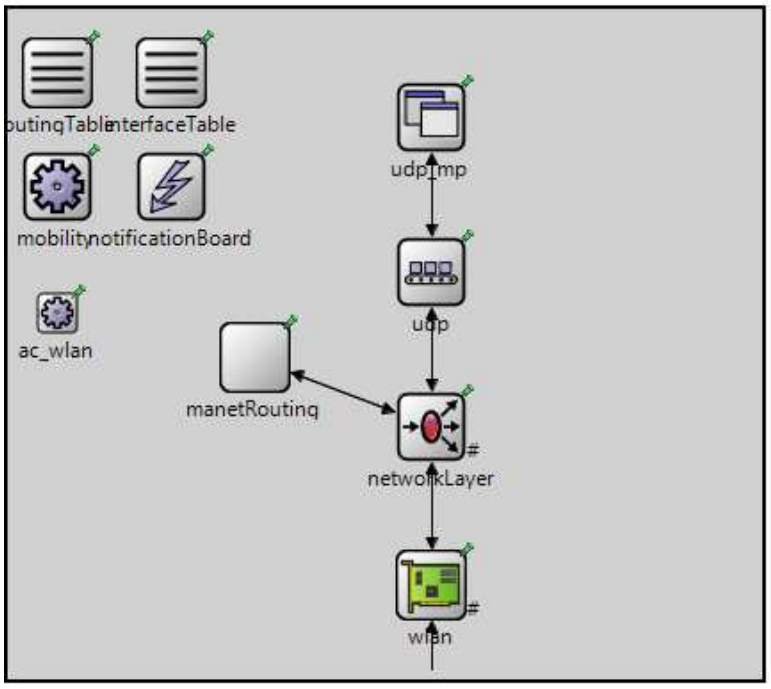


Figure 4.1: VANET node model in Omnet++

such as the channelControl and the FlatNetworkConfigurator, as well as the Annotations-Manager and the ObstacleControl module. These two modules must be enabled in the Omnet simulation configuration file and will work together to draw the buildings in the map. The obstacles simulator examines the wireless transmission present in the simulation and recalculate the strength of the signal based on what obstacles are in the path.

4.2 Simulator Communication

To communicate back and forth, TraCI clients and server use a set of messages. In figure 4.2 the standard message format is pictured. For the TraCI commands there are three basic groups [4].

The first group is used to control the simulation with the following commands:

- Simulation Step: signals the traffic simulator to perform the next step
- Status: sent as a request command's reply.

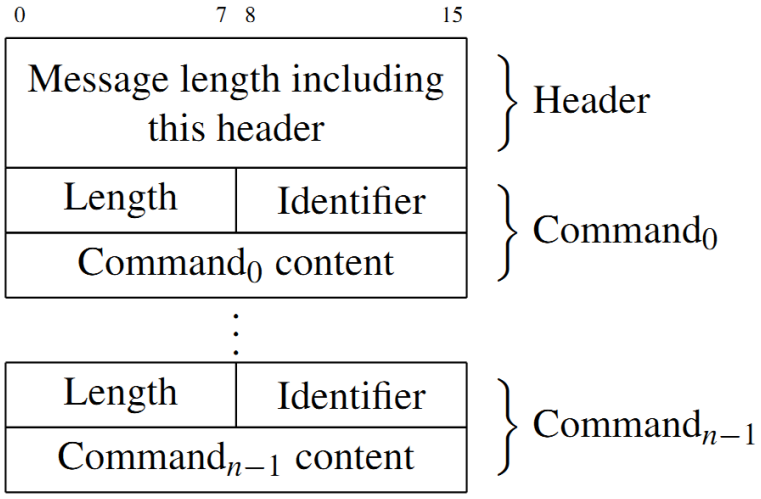


Figure 4.2: TraCI Message Format [4]

- Move Node: Contains new coordinates for a vehicle/node.

The second set of commands are used to control the mobility primitives of each vehicle. These commands effect a single vehicle and are :

- Set Max Speed
- Stop Node
- Change Lane
- Change Route
- Change Target (destination)

The third set of commands is used only for control of the simulation environment and gather information. These commands include:

- Scenario: Get the dimensions of the scenario
- Position Conversion: converts between Cartesisan coordinates and the appropriate position on the road network

- Driving Distance: Finds the distance on a path and the estimated time to get from one to another.

4.3 The Simulations

Once the setup of the simulator and the node is complete, the final step in the setup pertains to how the simulations will run. Three files are necessary to define the movement of the nodes in the mobility simulator, however, they will be loaded through Omnet++. The first file is the net file, 'simulation.net.xml', which defines the locations of the nodes in a traffic network. The route file, 'simulation.rou.xml', file defines the sequence of lanes that each node will follow for its entire path. Lastly is the SUMO configuration file (simulation.sumo.cfg) that defines how the simulation within SUMO is setup. For more information see [30] for how these files are setup. There are several tutorials that provide instructions on how to create a basic SUMO simulations as well as a very detailed user manual in the documents section. For the obstacles portion of the simulation, an 'obstacles.xml' file is used to define the locations of the buildings in the Omnet++ simulation.

Each traffic environment consists of a pair of traffic topology (called a net) and route files, the example traffic topologies can be seen in figures 4.3, 4.4, and 4.5. The city environment is nine blocks wide and nine blocks high with each block being 100m by 100m. The country environment is 10km wide with streets running in multiple directions. Lastly, the highway environment is 4km wide with the upper two lanes moving traffic in the left direction and the lower two lanes moving traffic in the right direction. Each traffic environment was simulated multiple times with two factors that changes: number of TxRx pairs and traffic density. A TxRx pair is a pair of nodes that communicate with each other. One of the two nodes is the sender and the other node is the receiver and all surrounding nodes are only used to forward packets from source to destination. For each set of simulation runs there was up to 10 TxRx pairs. The number of TxRx pairs was varied between one and ten sync pairs. Also, each time the simulations were run, the traffic density was changed.

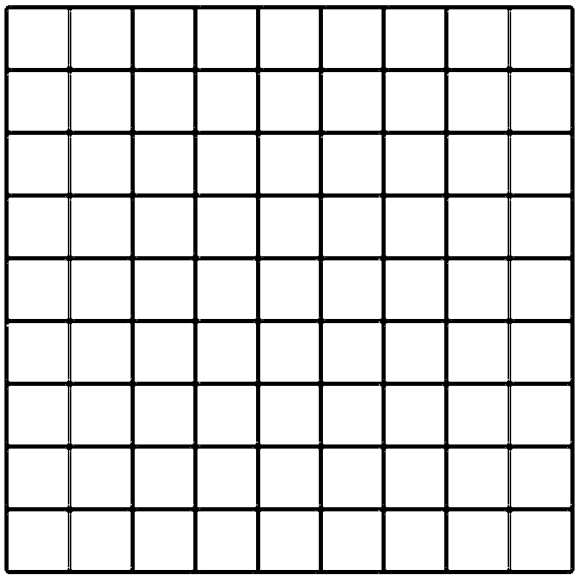


Figure 4.3: City Mobility Network

Simulations would start out with low density of 163 nodes, change to 247 nodes, and then 470 nodes. It was necessary to vary the traffic density in order to model how populated the streets would be during different times of the day. This allowed to show the differences in network performance while vehicle density was at different levels.

4.4 Evaluations

The simulations were run in five different sets. The only difference between each set was the number of transmit and receive (TxRx) pairs that existed in the network. The goal of varying the number of TxRx pairs was to create more data network traffic that would have in impact on how quickly a message could get delivered between TxRx pairs. Within each set of simulations there were 27 individual simulations that varied the scenario and routing protocol used. Nodes were simulated in the three previously mentioned scenarios and for each scenario all three routing protocols were simulated. The final parameter that changes in the simulations was the density of the traffic, which varied from high density (470 vehicles) to medium density (247 vehicles) and to low density (163 vehicles).

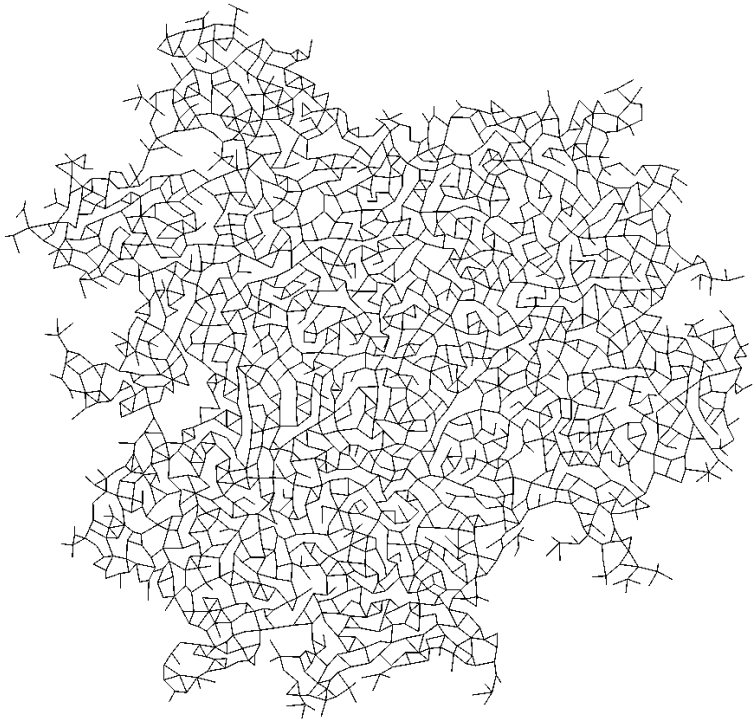


Figure 4.4: Country Mobility Network

Figure 4.5: Highway Mobility Network

From each simulation, the average throughput and latency were recorded for comparison of the protocols. This will allow for an in-depth analysis of the strengths and weaknesses of the routing protocols based on scenario and traffic density.

Chapter 5

Results and Analysis

The routing protocols used for evaluation in this thesis are AODV, DSR, and the DYMO protocols. Each protocol has had its own prior research, however, the three protocols were used for data network analysis in different traffic environments. This showed the strengths and weaknesses of each protocol when they were simulated in each of the different vehiclular traffic scenarios.

The routing protocols used in this work for evaluation are AODV and DSR. Research for DYMO has already been done, however, DYMO was evaluated and used as a control. Each of these protocols are designed differently, however, they are all designed for mobile ad-hoc networks which make them play an important role within a VANET. To evaluate each protocol in this work, they were implemented in nodes that represent individual vehicles on a road network. The vehicles were equipped with the ability to communicate with an IEEE802.11b wireless network with no central infrastructure for communications (i.e. ad-hoc). Since there are different types of road environments, nodes were simulated in a country, highway, and city environment. In the evaluation of each protocol, the use of three different road environments showed which protocol works best for fast changing environments and which protocols work bests for each specific environment.

Tables 5.1 and 5.2 were included to help aid in the analysis of the results. The charts presented in the following results section provide an easier way to compare the simulations, however, these tables provide the specific values associated with each simulation.

5.1 Throughput Results

The following section contains the throughput results from each of the simulations. All data is provided in tables at the end of this section. The throughput was calculated by monitoring the channel that the application transmits packets on and determining the speed at which the packets are successfully transmitted. The results for each simulation scenario are shown in figures 5.1, 5.2, and 5.3. The most noticeable result with these plots is that medium and low traffic density during simulation in country environment is missing. Due to the characteristics of a country environment, the nodes present in those two sets of simulations were unable to find a complete path to transmit the packets. Within the country environment the streets are a considerable distance away from each other, typically out of transmission range of other nodes. Also, the streets in the country environment are not parallel like in the city and highway environment. This causes the nodes to move in many directions compared to the parallel and perpendicular directions of the city and highway environment, giving the nodes an extremely limited time to communicate with each other. The high density traffic simulations for the country environment were the only country simulations that results in successful communication between the TxRx pairs.

The DSR routing algorithm proved to be the higher throughput transmitting algorithm in the high traffic density city simulations. The high density traffic simulations in the country environment did result in some communication between the nodes. The DSR routing protocol had the highest throughput with 5 TxRx pairs present on the map, the DYMO protocol remained the most stable throughout all 10 simulations. DYMO had one outlier with 4 TxRx pairs, however it increase as the more TxRx pairs were added. AODV did not remain as stable as DYMO in that it was oscillating from high to low throughput over the 10 simulations. AODV is the only routing protocol used in the simulations that does not cache route information in overheard transmissions.

The city environment simulations showed different results for the different traffic simulations. In the high density city simulations, the three routing protocols all started with a throughput of 1900 bits/ to 2400 bits/s with only a single TxRx pair. The AODV routing

protocol had the most drastic change, about 100bits/s, as the number of TxRx pairs were increased. The DSR routing algorithm remained stable with throughput between 2200 and 1750 bits/s. The addition of extra network traffic did not have as big of an effect on the overall throughput as it did with AODV. The DYMO protocol showed a similar dip in throughput as the AODV protocol in that there was almost a 1000bit/s drop. Even though the vehicles are slow moving, the changing city with the presences of buildings on either side of the street did have an effect on each of the protocols. The medium density traffic environment showed similar effects for each of the routing protocols. Looking at plot B in figure 5.1, each of the routing protocols started at a high throughput with 1 TxRx pair and finished at a level that was between 500 and 1500 bit/s lower with 10 TxRx pairs. DSR showed the lower loss in throughput for the 10 simulations. The change to a low traffic density environment caused the routing protocols to act differently. With few vehicles present in the traffic environment, it creates fewer hop paths from source to destination. The DYMO protocol had an increase in throughput from four to seven TxRx pairs because of this, however, as the number of TxRx pairs increased the throughput dropped to a level similar to where it started with a single TxRx pair.

The plots in figure 5.2 show the results obtained from the high, medium, and low density highway simulations. The DYMO protocol showed an increase in throughput as the number of TxRx pairs increased. The increase in the TxRx pairs causes an increase in the number of nodes trying to communicate with each other, which causes the number of route discoveries to be increased. This increase helps DYMO learn of more routes which allows the nodes to send out their packets with an increased probability that a route already exists. The AODV and DSR protocols do not experience this in the high and medium traffic density scenarios. The low traffic density network has a different effect on the nodes because vehicles are spaced farther apart. The DYMO protocol no longer has the positive slope it did with the prior simulation and AODV actually gains throughput as the number of TxRx pairs increase because of the less dense spacing of the vehicles.

5.2 Latency Results

The latency results are important for applications that are time sensitive, such as collision avoidance or emergency vehicle warning. These latency measurements were calculated by determining the time between when the message left the sender and was received at the destination.

In figures 5.4, 5.5, and 5.6located at the end of this section the latency results are shown for simulations with multiple TxRx pairs in different low, medium, and high denesity traffic environments. These are the same environments used in the throughput simulations. Recall from the throughput simulations that the nodes in a country environment during medium and low traffic density were not able to achieve an end to end route so the latencies were not shown on plots figures because they are infinite. The nodes do have communication among themselves, however, the source and destination nodes are not able to communicate with each other so this is why the latency would be considered infinite.

In all seven plots, the most noticeable result is that the DSR routing protocol has the highest average latency in all of the simulations and DYMO having the lowest latency. The city environment resulted in some of the lowest latencies for DSR that ranged between 1.5 seconds and 6 seconds. The highway and country scenarios are the environments that resulted in much higher latencies. For each of the highway environments, the DSR routing protocol had the highest latency when the TxRx pairs remained low. As the pairs increased, the latencies tended to decrease which is due to the amount of network traffic generated from the increasing number of pairs and the ability to cache routes.

The second lowest latency routing protocol is the AODV protocol. This protocol typically had latencies that were under three seconds, which is a big difference in comparison to DSR. The DYMO routing protocol also had very low latencies, typically less than one second in all scenarios. When both of these protocols are compared back to the DSR protocol, there is a distinct difference between them.

High Traffic Density - Throughput (bits/s)									
	AODV			DSR			DYMO		
TxRx Pai	City	Country	Highway	City	Country	Highway	City	Country	Highway
1	2382.72	382.11	561.65	1861.04	370.45	673.99	1964.10	180.14	348.75
2	2003.46	360.01	654.59	2269.89	135.67	769.07	2010.51	163.41	355.49
3	1932.24	315.99	859.63	1816.32	389.78	1186.50	1366.60	135.29	576.27
4	1407.60	80.08	683.42	2220.79	185.24	446.48	1854.43	384.89	1213.97
5	1691.66	351.50	754.86	1747.70	459.55	1032.33	1312.60	167.53	713.94
6	1774.08	333.18	787.16	1900.41	202.35	939.90	1263.93	265.13	1118.34
7	1671.43	166.59	467.94	1458.22	415.25	979.31	1118.02	284.76	1277.23
8	1496.35	323.55	662.90	1845.26	311.48	1018.71	1257.26	304.38	1436.12
9	1671.90	242.66	833.94	1817.68	378.92	1058.12	1307.85	324.01	1595.01
10	1336.50	194.13	811.65	1790.10	319.46	1097.53	1389.56	343.63	1753.89

Medium Traffic Density - Throughput (bits/s)									
	AODV			DSR			DYMO		
TxRx Pai	City	Country	Highway	City	Country	Highway	City	Country	Highway
1	3337.90	0.00	504.71	2103.78	0.00	998.27	2074.42	0.00	721.38
2	3068.89	0.00	504.71	2710.09	0.00	491.56	2492.64	0.00	659.93
3	2571.51	0.00	738.03	2323.66	0.00	524.46	2135.76	0.00	901.74
4	2089.63	0.00	961.43	1789.72	0.00	480.91	1548.03	0.00	900.73
5	1752.49	0.00	664.65	1600.53	0.00	532.33	1555.64	0.00	872.22
6	1835.66	0.00	437.62	1140.35	0.00	422.25	1366.65	0.00	973.95
7	2064.03	0.00	555.39	1235.24	0.00	525.21	1168.43	0.00	1028.20
8	1599.83	0.00	605.99	1182.36	0.00	499.33	1289.35	0.00	1082.44
9	1401.34	0.00	690.35	1175.16	0.00	485.22	771.99	0.00	1136.69
10	1475.56	0.00	727.40	1354.51	0.00	510.24	573.78	0.00	1190.94

Low Traffic Density - Throughput (bits/s)									
	AODV			DSR			DYMO		
TxRx Pai	City	Country	Highway	City	Country	Highway	City	Country	Highway
1	1821.31	0.00	239.59	1786.64	0.00	444.26	1703.54	0.00	1233.91
2	1538.94	0.00	538.27	1530.87	0.00	976.54	1661.86	0.00	373.12
3	1184.09	0.00	619.55	2438.52	0.00	804.88	1156.18	0.00	908.28
4	1601.26	0.00	550.14	1344.30	0.00	461.13	2457.02	0.00	434.29
5	1115.11	0.00	705.62	1540.07	0.00	599.08	2313.06	0.00	667.63
6	1697.62	0.00	781.83	1524.16	0.00	595.45	2462.59	0.00	701.25
7	1486.87	0.00	871.10	1456.19	0.00	574.87	1864.64	0.00	719.56
8	1130.68	0.00	887.90	1745.32	0.00	554.29	1645.85	0.00	687.25
9	930.36	0.00	880.15	1320.25	0.00	533.72	1621.65	0.00	645.98
10	854.62	0.00	861.26	1252.28	0.00	513.14	1597.56	0.00	705.35

Table 5.1: Throughput results for the high, medium and low traffic density scenarios

High Traffic Density - Latency (s)									
	AODV			DSR			DYMO		
TxRx Pai	City	Country	Highway	City	Country	Highway	City	Country	Highway
1	0.181	1.438	0.865	4.930	10.020	23.239	0.076	0.005	0.094
2	0.541	0.003	0.784	1.520	14.604	14.838	0.003	0.022	0.009
3	0.308	0.017	0.879	1.889	9.816	15.053	0.004	4.248	0.045
4	0.163	0.065	2.061	2.027	20.103	11.568	0.004	0.003	0.009
5	0.304	0.003	1.011	2.558	2.558	8.906	0.067	0.005	0.012
6	0.360	0.852	0.471	2.812	8.593	5.140	0.026	0.056	0.010
7	0.189	0.059	1.027	3.137	7.650	6.468	0.024	0.951	0.148
8	0.651	0.635	0.945	2.217	6.708	7.214	0.043	0.155	0.076
9	0.660	0.570	0.738	2.784	5.766	5.486	0.021	0.068	0.043
10	0.774	0.658	0.673	3.135	8.423	5.932	0.034	0.132	0.056
Medium Traffic Density - Latency (s)									
	AODV			DSR			DYMO		
TxRx Pai	City	Country	Highway	City	Country	Highway	City	Country	Highway
1	0.270	-	1.147	3.664	-	6.448	0.005	-	0.092
2	0.066	-	0.459	1.944	-	14.878	0.003	-	0.006
3	0.317	-	0.553	2.910	-	4.507	0.039	-	0.011
4	0.551	-	1.061	5.738	-	8.174	0.008	-	0.014
5	0.293	-	3.296	4.800	-	3.962	0.006	-	0.101
6	0.268	-	1.067	2.630	-	5.003	0.014	-	0.052
7	0.202	-	0.611	4.814	-	6.821	0.015	-	0.055
8	0.921	-	0.597	4.165	-	4.459	0.016	-	0.057
9	0.789	-	0.615	5.168	-	4.187	0.017	-	0.060
10	0.652	-	0.593	3.646	-	3.914	0.017	-	0.062
Low Traffic Density - Latency (s)									
	AODV			DSR			DYMO		
TxRx Pai	City	Country	Highway	City	Country	Highway	City	Country	Highway
1	0.05256	-	0.00570	3.65177	-	16.77000	0.00562	-	0.00226
2	0.34078	-	0.49850	3.78901	-	10.11263	0.00270	-	0.00688
3	0.68046	-	0.27890	3.46500	-	7.89600	0.00491	-	0.00429
4	0.52546	-	0.51420	3.06758	-	8.22605	0.00274	-	0.01351
5	0.35974	-	0.83384	3.20982	-	7.11662	0.00833	-	0.00429
6	0.466928	-	0.75851	2.95504	-	6.96684	0.00650	-	0.00945
7	0.27701	-	0.94649	2.79450	-	6.57714	0.00704	-	0.01052
8	0.280103	-	1.06865	2.63397	-	6.18745	0.00759	-	0.01159
9	0.428308	-	1.190802	2.47344	-	5.79776	0.00814	-	0.01265
10	0.448368	-	1.31296	2.31290	-	5.40807	0.00868	-	0.01372

Table 5.2: Latency results for the high, medium and low traffic density scenarios

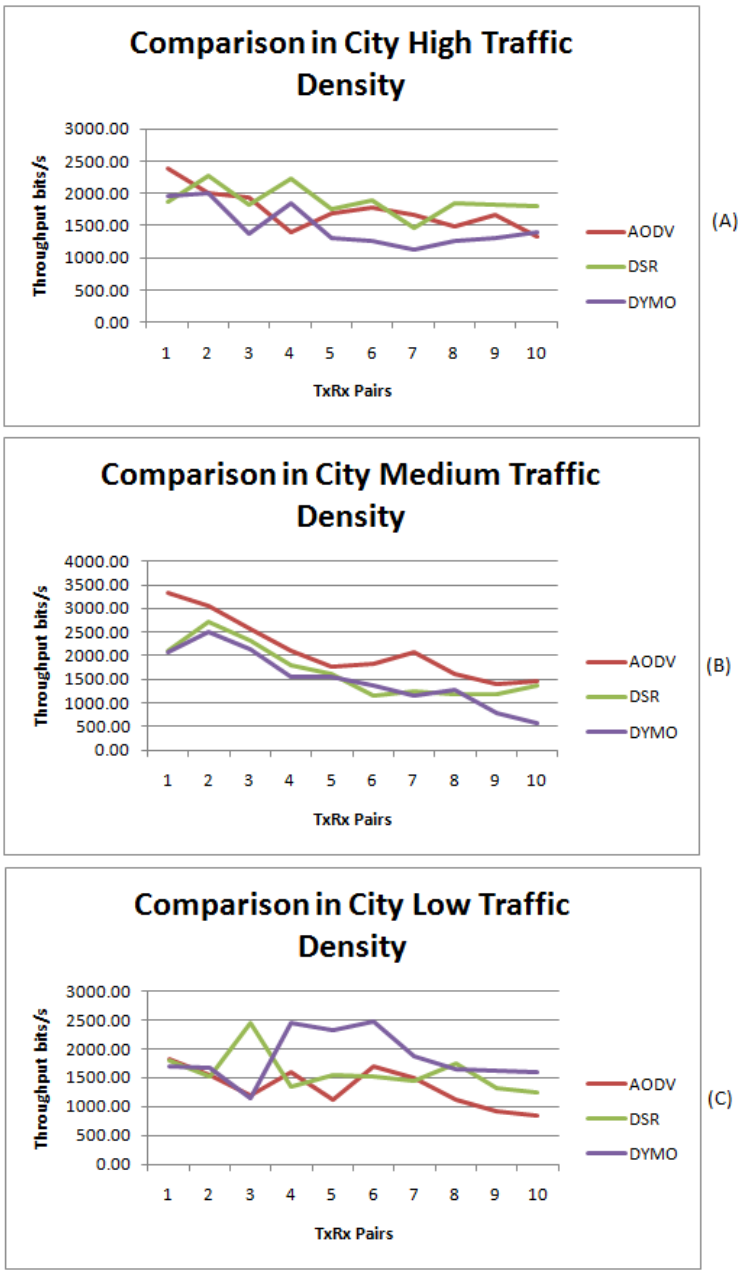


Figure 5.1: Throughput in bits/second for city environment

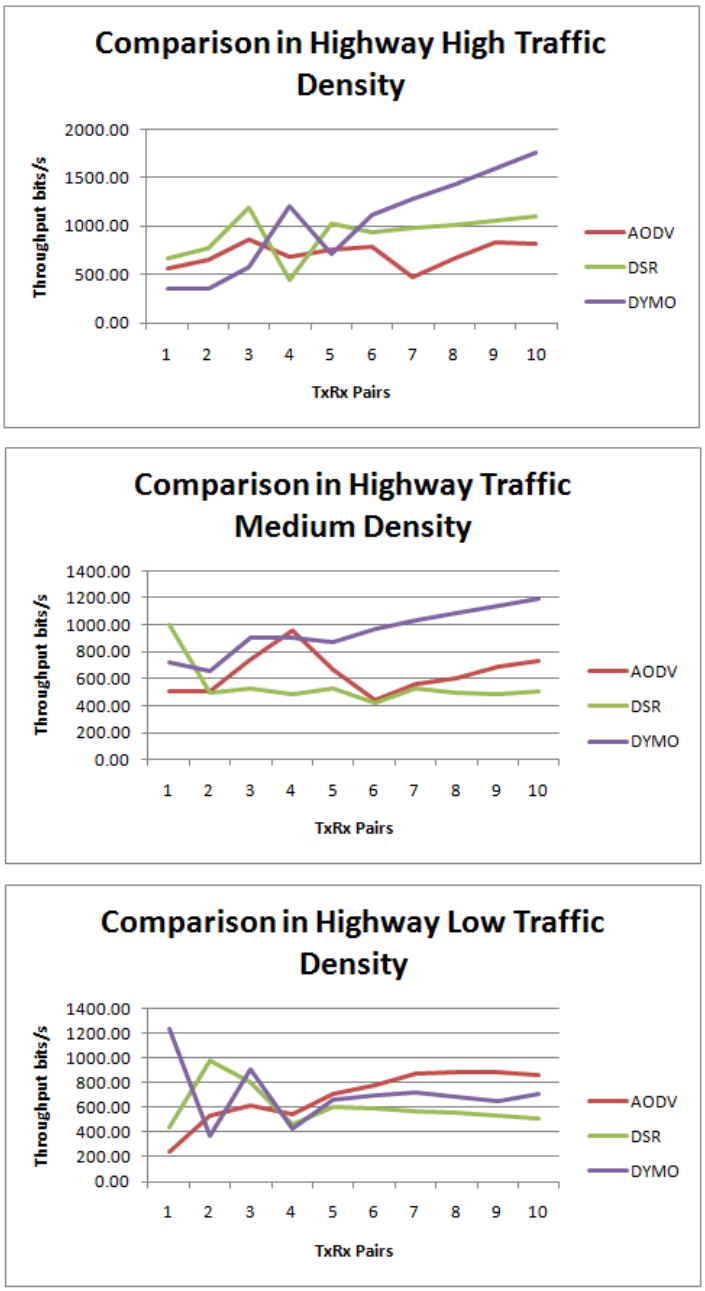


Figure 5.2: Throughput in bits/second for highway environment

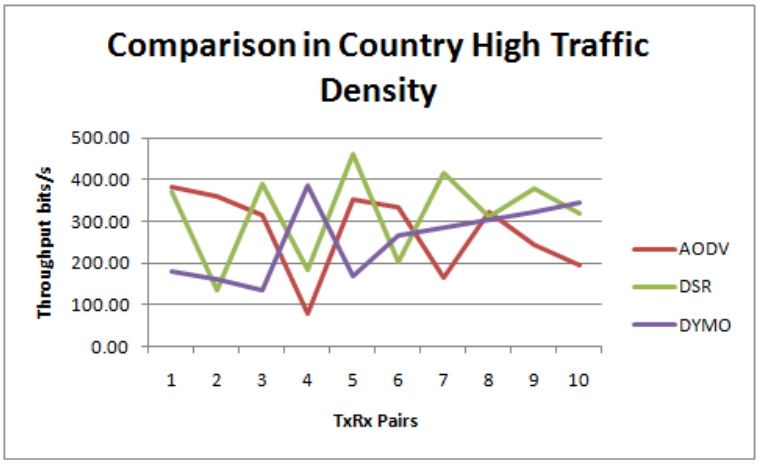


Figure 5.3: Throughput in bits/second for country environment

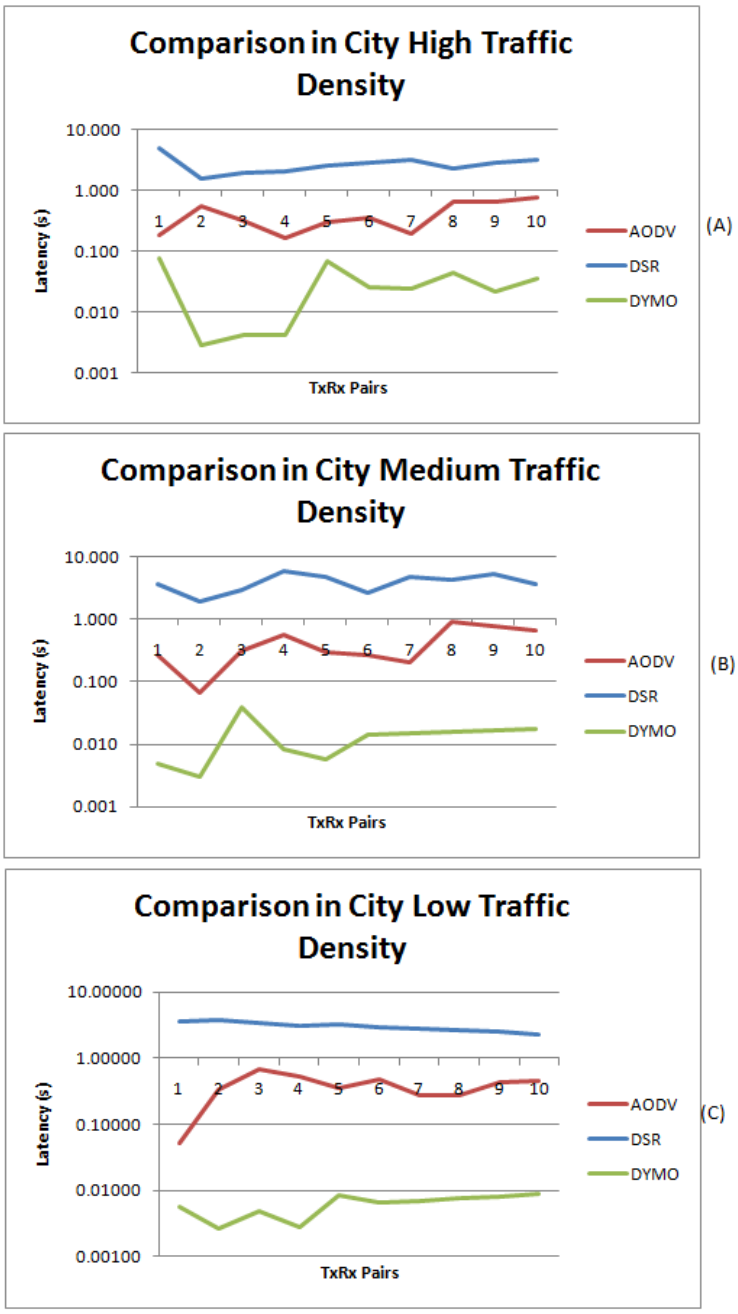


Figure 5.4: Latency in seconds for city environment

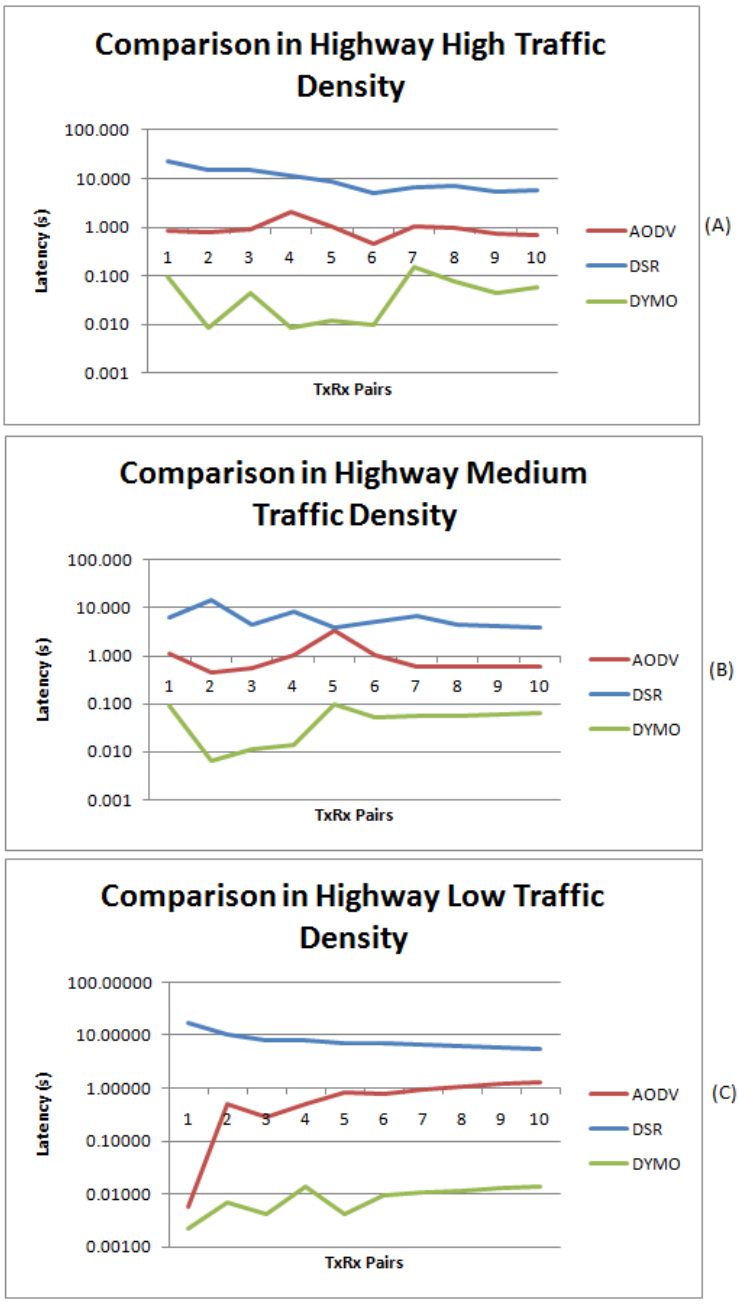


Figure 5.5: Latency in seconds for highway environment

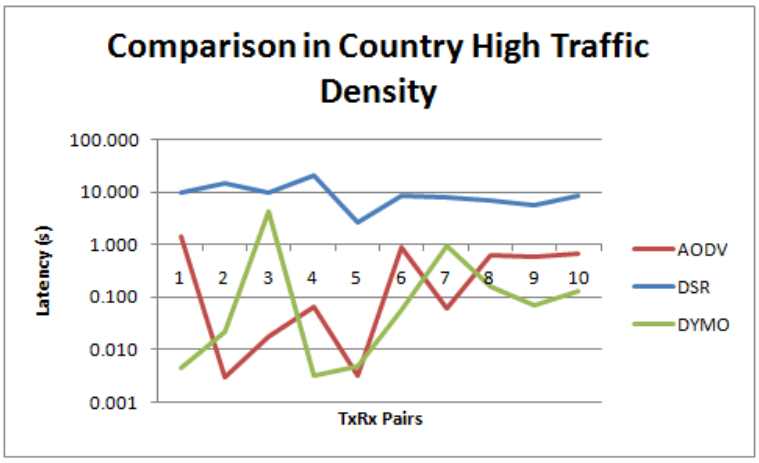


Figure 5.6: Latency in seconds for country environment

Chapter 6

Conclusions

In conclusion, the VANET simulator that was developed in this work proved to provide quick simulations. By using TraCI to manage the separate simulators, the traffic and network simulators were allowed to work separately while remaining completely in sync. The use of obstacles in the network simulations provided for accurate simulations because it limited the range a node could transmit packets. This was particularly useful in the city simulations because of the presence of buildings on each block.

The results from the simulations showed some interesting results that help determine how the routing protocols should be used. The DYMO routing protocol is best used in application where latency (time to find a route and deliver the message) needs to be extremely low. With DYMOs ability to cache routes and assume bidirectional paths, this routing protocol is ideal for low latency situations. AODV is another routing protocol that could be used in VANET applications because it also maintains a relatively low latency, even though not as low as DYMO, that would allow it to be applicable for VANET applications. The DSR routing algorithm proved to be a poor choice for a routing protocol in VANET applications because of the high latencies that are associated with it. Latencies as high as twenty three seconds in a highway situation are not even close to a tolerable latency for applications in such a high speed environment. Twenty three seconds, or even ten seconds, is too long of a time for a message to be delivered in a VANET application and could result in important safety information arriving to the vehicle too late. For VANET applications, there needs to be little latency so information can be delivered from node to node as quick

as possible in order to provide enough time for the driver to react. Take, for example, an intersection collision avoidance application. As a vehicle approaches an intersection it needs to gather information about other vehicles, their location, and their velocity in order to determine if any of the vehicles will cross the source vehicles path. If so, the driver needs to be warned in order to take preventative action. If information is delayed, it could result in an accident.

After analysis of the throughput results, its clear that each routing protocol performs differently in each type of traffic environment. It is also clear that there are certain traffic environments that are not suited for VANET applications. A city environment is one traffic topology that is well suited for each of these routing protocols. Throughputs ranged from about 500 bits per second to over 3000 bits per second in the city environments. This is good for applications that need to transfer large amounts of data and even better for applications that need to transfer smaller amounts of data. Highway environments had throughputs from each of the routing protocols that were lower than those in the city environments, however, they were still about 300 to 1700 bits per second which would allow for applications to transfer messages between nodes. The country environment is clearly not meant for VANET applications because it was only able to have nodes communicate when the traffic density was high. As the density thinned out in the medium and low simulations, nodes were not able to establish a path between source and destination to transmit messages. With a country environments characteristics of streets placed far apart and faster moving vehicles, it will be hard for end to end communication to occur, therefore, not being suitable for applications that need reliable connections. In order to allow VANET applications to work in this environment another type of wireless network must be used that allows for longer transmission ranges or use a modified IEEE802.11 radio with increased transmission power.

Overall, the DYMO routing protocol seems to be the best choice for a routing protocol because of its very low latencies and throughput comparable to other protocols. The

AODV routing protocol is a good second choice for a routing protocol, however, its latencies averaged higher than DYMO but are still within a reasonable range. It would be suggested to use this protocol in situation where network latencies may not be as important. The DSR protocol is not recommended for VANET application use because of its very high latencies. Also, as previously stated, the best environment for VANET applications is the city network because of its high throughput and slow changing topology. A highway environment is also acceptable for VANET application but larger amounts of data will be transferred slower due to decreased overall throughput.

Chapter 7

Future Work

This work provided a robust simulator for VANET applications and a comprehensive analysis of some of the available routing protocols that could be used for VANET applications. There are several suggestions that could be made to help aid in even more efficient simulations in the future. The first is to adapt SUMO and Omnet++ to work in a multi-processor environment. The simulations for this work were run on a standard PC, however, they could be made to support much larger environments that simulate in quicker time if the software is adapted to a cluster or multiple core PC with the use of software such as MPI. The other possibility for future work is to create a wider variety of traffic environments for simulations. Even though a city, a highway and a country environment were simulated, not all traffic environments are the same as defined for these simulations. Other future work could expand upon this research by constructing multiple VANET systems that could be placed into a vehicle and tested on real roads. This would verify the findings of this thesis as well as provide researchers at RIT some baseline hardware to implement other VANET research on, such as multiple radio interfaces and various applications.

Bibliography

[1] W. Chen and T. Technologies, "Ad Hoc Peer-to-Peer Network Architecture for Vehicle Safety Communications," *IEEE Communications Magazine*, pp. 100–107, April 2005.

[2] C. Sommer and I. Dietrich, "Simulation of Ad Hoc Routing Protocols using OMNeT ++ A Case Study for the DYMO Protocol," *Springer Science Business*, 2009.

[3] D. B. Johnson and D. A. Maltz, "DSR : The Dynamic Source Routing Protocol for Multi-Hop Wireless Ad Hoc Networks," *Discovery*, vol. 5, pp. 1–25, 2001.

[4] S. Fischer, J.-p. Hubaux, A. Wegener, M. Pi, M. Raya, and H. Hellbr, "TraCI : An Interface for Coupling Road Traffic and Network Simulators," *Proceedings of the 11th Communications and Networking Simualtion Symposium*, pp. 155–163, 2008.

[5] A. K. Saha and D. B. Johnson, "Modeling mobility for vehicular ad-hoc networks," *Proceedings of the first ACM workshop on Vehicular ad hoc networks - VANET '04*, p. 91, 2004. [Online]. Available: http://portal.acm.org/citation.cfm?doid=1023875.1023892

[6] S. Yousefi, M. S. Mousavi, and M. Fathy, "Vehicular ad hoc networks (vanets): Challenges and perspectives," in *ITS Telecommunications Proceedings, 2006 6th International Conference on*, 2006, pp. 761 –766.

[7] S. Jaap, M. Bechler, and L. Wolf, "Evaluation of routing protocols for vehicular ad hoc networks in city traffic scenarios," in *in Proc of the 11th EUNICE Open European Summer School on Networked Applications, Colmenarejo*, 2005, pp. 584–602.

[8] H. Hartenstein, M. Lott, M. Radimirsch, and D. Vollmer, "Position-Aware Ad Hoc Wireless Networks for Inter-Vehicle Communications : the Fleetnet Project," *Proceeding MobiHoc '01 Proceedings of the 2nd ACM international symposium on Mobile ad hoc networking computing*, pp. 259–262, 2001.

[9] NOW, “Networks on wheels,” Jan. 2011. [Online]. Available: http://www.network-on-wheels.de/contact.html

[10]

[11] W. C. Taek Jin Kwon, “Unicast Routing among Local Peer Group (LPG) -based VANETs,” *GLOBECOM Workshops*, pp. 1–5, 2008.

[12] G. Sklyarenko, “AODV Routing Protocol,” *Proceedings from Technische Informatik*, pp. 1–13, 2008.

[13] S.-J. Lee, E. M. Belding-Royer, and C. E. Perkins, “Ad hoc on-demand distance-vector routing scalability,” *ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 6, no. 3, p. 94, Jun. 2002. [Online]. Available: http://portal.acm.org/citation.cfm?doid=581291.581306

[14] C. E. Perkins, E. M. Belding-royer, S. Das, and B. Min, “Ad-Hoc On-Demand Distance Vector (AODV) Routing,” *Internet Engineering Task Force*, vol. 1, no. February 1999, 1997.

[15] J. Raju and J. Garcia-Luna-Aceves, “A new approach to on-demand loop-free multipath routing,” *Proceedings Eight International Conference on Computer Communications and Networks (Cat. No.99EX370)*, pp. 522–527, 2007. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=805568

[16] I. Chakeres and E. Belding-Royer, “AODV routing protocol implementation design,” *24th International Conference on Distributed Computing Systems Workshops, 2004. Proceedings.*, pp. 698–703, 2004. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=1284108

[17] J. Jubin and J. Tornow, “The DARPA packet radio network protocols,” *Proceedings of the IEEE*, vol. 75, no. 1, pp. 21–32, 1987. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=1457970

[18] P. C. Chakers I., “Dynamic MANET On-demand Routing (DYMO),” no. 21, 2010. [Online]. Available: http://tools.ietf.org/id/draft-ietf-manet-dymo-21.txt

[19] C. Sommer, I. Dietrich, and F. Dressler, “Simulation of Ad Hoc Routing Protocols using OMNeT++,” *Mobile Networks and Applications*, pp. 786–801, Jun. 2009. [Online]. Available: http://www.springerlink.com/index/10.1007/s11036-009-0174-5

[20] S. Wang, “Implementing and evaluating three routing protocols in dual-radio-dual-mode IEEE 802.11(b) wireless mesh networks,” *Computer Communications*, vol. 31, no. 10, pp. 2596–2606, Jun. 2008.

[21] C. Sommer, I. Dietrich, and F. Dressler, “Realistic Simulation of Network Protocols in VANET Scenarios,” *2007 Mobile Networking for Vehicular Environments*, pp. 139–143, 2007. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=4300819

[22] A. Hassan, “VANET Simulation,” Ph.D. dissertation, School of Information Science, Halmstad University, 2009.

[23] “The network simualtor - ns-2,” Jan. 2011. [Online]. Available: http://isi.edu/nsnam/ns/

[24] “Ns-3 discrete even network simulator,” Jan. 2011. [Online]. Available: http://www.nsnam.org/

[25] S. Ray, “Realistic Mobility for MANET Simulation,” Ph.D. dissertation, Regional Engineering College, Trichy, India, 1999.

[26] A. Varga, “THE OMNET ++ DISCRETE EVENT SIMULATION SYSTEM,” *The European Simulation Conference ESM 39*, pp. 319–324, 2010.

[27] A. L. Santos and F. Milagro, “Experimental demonstration of the viability of IEEE,” *Proceedings of the 4th International Conference on Testbeds and research infrastructures for the development of networks communities*, 2008.

[28] D. Krajzewicz, M. Hartinger, G. Hertkorn, P. Mieth, J. Ringel, C. Rssel, and P. Wagner, “The ”Simulation of Urban MObility” package : An open source traffic simulation,” in *2003 European Simulation and Modelling Conference*, 2003. [Online]. Available: http://elib-v3.dlr.de/21385/1/dkrajzew_ESMc2003.pdf

[29] “Open street maps:free editable map of the whole world,” Jan. 2011. [Online]. Available: http://www.openstreetmap.org

[30] “Simulation of urban mobility,” Jan. 2011. [Online]. Available: http://sumo.sourceforge.net/

[31] D. R. Choffnes and F. E. Bustamante, “An integrated mobility and traffic model for vehicular wireless networks,” *Proceedings of the 2nd ACM international workshop on Vehicular ad hoc networks - VANET ’05*, p. 69, 2005. [Online]. Available: http://portal.acm.org/citation.cfm?doid=1080754.1080765

[32] R. Mangharam, D. Weller, D. Stancil, R. Rajkumar, and J. Parikh, “GrooveSim: a topography-accurate simulator for geographic routing in vehicular networks,” in *Proceedings of the 2nd ACM international workshop on Vehicular ad hoc networks*. ACM, 2005, pp. 59–68. [Online]. Available: http://portal.acm.org/citation.cfm?id=1080764

[33] H. Phule, “Thesis draft: Evaluation of physical layers for vehicular ad-hoc networks,” Jan. 2011.